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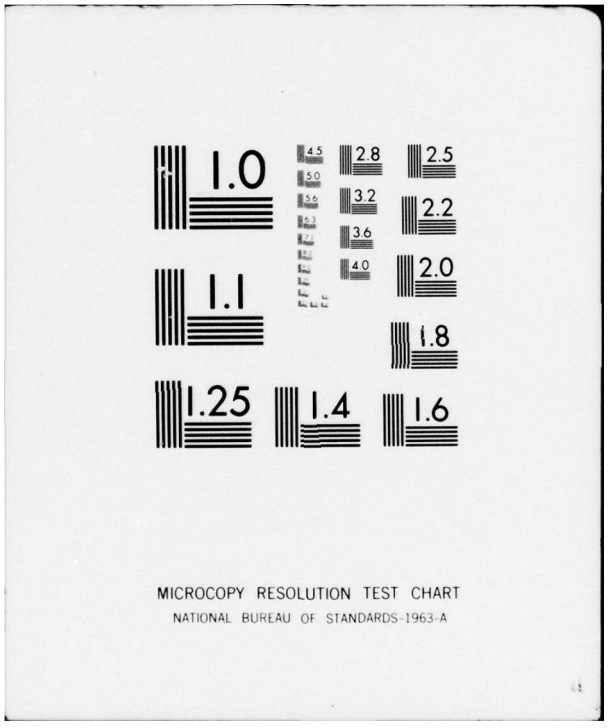
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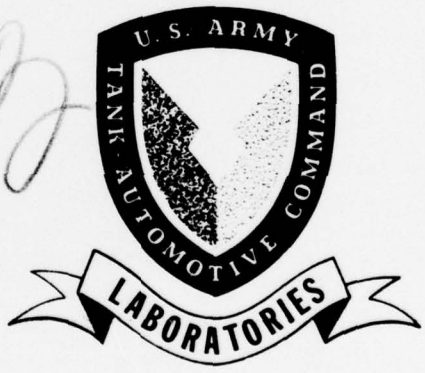
TECHNICAL REPORT NO. 12121

AD A040424

MEASUREMENT OF TEMPERATURES DEVELOPED IN TENSILE BARS UNDER TEST TO FRACTURE



DECEMBER 1975

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by EDGAR B. SINGLETON

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Contract DAAE07-75-M-2132

TACOM

MOBILITY SYSTEMS LABORATORY

U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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TECHNICAL REPORT No. 12121

MEASUREMENT of TEMPERATURES DEVELOPED in TENSILE BARS UNDER TEST to FRACTURE

by

Edgar B. Singleton

December 1975

Contract DAAE07-75-M-2132

Department of Physics
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ABSTRACT

Mild steel tensile bars are hardened and tempered and pulled to fracture. The temperature generated within the tensile bars is measured with a scanning infrared radiometer and liquid crystals. Radiometer tracings and photographs of the liquid crystals are presented which show an intense localized heating present in the necked region of the tensile bars.

A temperature anomaly expected on the basis of past work was not observed.

A concept, in its preliminary stage, is presented to describe the apparent temperature anomaly in terms of a crystal model potential energy function.

Suggestions are made to continue the work.

FOREWARD

The work presented here was carried out at Bowling Green State University, Department of Physics, between 2 June L975 and 15 December 1975, under the supervision of the Applied Physics Sub-function (ATTN: AMDTA-RHR), US Army Tank- Automotive Command, under Contract DAAE07-75-M-2132.

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OBJECTIVE

The over-all scope of the work of which this report is a part is a more thorough understanding of work hardening, fatigue, and fracture in metals. This report pertains to the measurement of temperatures developed in hardened steel test samples while undergoing tensile strain to fracture. In particular an attempt is made to verify apparently anomalous temperature profiles reported in Technical Report 11602, July 1972, issued by TACOM (Reference 1).

Technical Report 11602, July 1972, issued by TACOM is concerned with the application of infrared radiometric techniques as a temperature measuring device during stress analysis of metals. In particular, one part of the research was concerned with tensile tests of standard cylindrical tensile bars of a common mild steel (SAE 4130). The sample bars were machined, some were hardened and tempered to selected hardness values and then all were ground to ASTM-E8 standards. The sample bars were all pulled to fracture using standard engineering techniques to record stress-strain relationships, elongation, reduction in area, etc. In addition, during the tensile test a scanning radiometer recorded the surface temperature of a small area (0.04 in^2) of the test section of the bar as a function of position along the bar. Each recorded scan of the test section was completed in 0.8 seconds. The tests were completed to fracture usually in just over one minute.

Some general characteristics of the temperature profile of all the tensile bars can be noted. During elastic strain a slight temperature drop was observed which can be predicted from thermodynamic considerations. During plastic deformation a general heating occurs and continues until fracture. Just before fracture occurs a region of the test bar will begin to show a drastic reduction in area. This is the so-called necking region and is characteristic of all ductile materials. Brittle materials tend to fracture without significant necking occuring. The hardening process that some of the test bars received increased their tensile strength but did not make them less ductile so that necking was observed in all samples before fracture occured. The temperature profile of the hardened samples, however, was different from the unhardened samples. In the necking region of the hardened samples a distinct temperature drop was recorded. The temperature began to drop when the necking began and continued to drop until fracture occured. In one such sample the temperature in the necking area apparently dropped below ambient room temperature.

A preliminary, and granted, incomplete, search of metallurgical literature fails to reveal any mention of a temperature drop under these circumstances.

When one seeks a description of the mechanics of this temperature drop one aspect of the experimental procedure imposes itself. Perhaps the temperature drop is not real but rather an instrumental parameter introduced by the radiometric techniques, and for some reason shows up as a characteristic only of the hardened samples.

The radiometer records temperature by analysis of infrared radiation emitted from a small surface area of the sample. Temperature variations would be recorded by the radiometer if the area of the sample changed in such a way that the area did not fill the optics of the radiometer. A change in emissivity of the surface would produce an indicated temperature change. In response to these possibilities one notes that in the reduced area of the necking region, while the area was different for each sample, the area was not reduced sufficiently to be less than the field of view of the radiometer. All of the samples were spray painted with flat-black lacquer to increase the emissivity of the surface and to promote a uniform emissivity for each sample. In addition, scanning electron microscope pictures (not in TACOM report) of the hardened and unhardened sample bars have been obtained and no immediately apparent difference can be seen in the surface structure of the metal to account for the difference in emissivity of the metal surface under the lacquer, in case that should be of consequence.

Every case in which instrumental parameters might be a possible explanation of the temperature drop seemed to be discounted.

It is possible that the temperature drop is real and has never been observed or reported before. If it is real then it represents thermal energy being converted to some form of stored energy, say, in the form of grain boundary surface energy, with a local decrease in entropy.

Before investigating the metallurgy or solid state physics that might describe this phenomenon we proposed one further experimental effort. This was to repeat the experiment to obtain contact temperature readings of similar sample bars under similar tensile testing. If the temperature drop was observed with contact temperature measurements it would strengthen the case for radiometric temperature measurements and perhaps contribute new knowledge to the science of metals.

Contact temperatures are obtained by the application of a new temperature measuring technique using liquid crystals and colored motion picture photography. In addition a scanning infrared radiometer records the temperature profile of the bar under test each second during the test to attempt to reproduce the data reported in Reference 1.

RESULTS

The temperature profiles recorded by the scanning infrared radiometer failed to reveal the temperature anomaly discussed in the OBJECTIVE of this report. In fact, intense local heating was observed as the tensile bar began to neck and this localized heating continued until fracture.

The liquid crystals, which were chosen on the basis of temperatures reported in Reference 1, were not sufficiently high temperature range to record the actual temperature of the heated zone but they did report simply that the zone became hot and remained out of the temperature range of the liquid crystals until fracture.

All tests which could compare the physical properties of the present test bars and those test bars available from Reference 1 reveal no difference between the bars. These tests included the standard engineering data available during the course of the actual tensile tests plus scanning electron microscope pictures to 10,000 X of the surface of the necked region and metallographical microphotographs of the strained and unstrained regions of the test bars.

DISCUSSION of RESULTS and RECOMMENDATIONS

On the basis of the statements made under RESULTS it would appear that the temperature anomaly is not real. In addition, the intense heating observed in the necking region is what one might expect on the simple basis of work being done on the sample bar as it elongates.

With these results in hand we returned to an analysis of experimental techniques as a possible source of the temperature anomaly. In spite of best efforts to date, we can not reproduce instrumental parameters, associated with the infrared radiometer, which could have erronously produced the selective temperature variations reported in Reference 1.

To the author the temperature drop reported in Reference 1 remains an anomaly.

There is no doubt that the sample bars used in the present work became hot in the necking region during strain to fracture. However, because it is apparently impossible to force the radiometer to record a decrease in temperature when an increase actually occurs, we are not prepared to state absolutely that the sample bars in Reference 1 did not get cold under what appears to be similar circumstances. Two factors contribute to this last statement:

1. The scanning electron microscope pictures and the metallographical microphotographs of the sample bars from Reference 1 were taken three years after the experiment had been completed. Relaxation or aging processes could have taken place in the metal during a three year interval which could destroy what may have been a momentary crystal structure associated with the decreased temperature that was apparently observed.

2. One can conceptualize an atomic model of a crystal structure which, when strained to conditions imagined to exist in the metal during the necking process, yields a potential energy curve for the simple model that under certain conditions would allow kinetic energy of the atoms in the crystal (which would appear as heat to the radiometer) to be stored momentarily as potential energy in the electric field of the crystal. Momentarily, because a quantum mechanical tunneling process would undoubtedly allow the crystal to return by a relaxation process to a lower more stable energy configuration and after this process had been completed the crystal would be identical to one in which the energy storage had not taken place. Whether or not the energy storage takes place (according to the model) depends on force constants in the crystal and the amount of work done on an atom in the crystal by the forces producing the strain before an atomic 'fracture' takes place releasing the atom to respond to the restoring forces within the crystal.

This model is not well enough developed to report further on here. It is, however, in light of the uncertainty remaining from the present work, the basis of a recommendation that work should proceed on the development of a model accompanied by selected experiments in an attempt to remove once and for all the anomaly from the description of the cold region in the tensile test bar.

EXPERIMENTAL PROCEDURES and TECHNIQUES

Tensile Bar Test Samples

The tensile bars were made from 1 1/8 in hexagonal bar stock which had the original mill markings as SAE 4130 with Military Specifications 6758, Cond. F4, CF. Thus the bar stock had been tempered and hardened (Cond. F4) and cold finished (CF). Oversize samples were cut from the bar stock and hardened and tempered by heating to 1625 F in an endothermic atmosphere gas fired furnace for one hour, then oil quenched and tempered out to selected hardnesses in a gas fired furnace at 700 F. Eight tensile bars were hardened in this manner, in pairs, and measured, by the heat treating company, to have the following hardnesses (averaged over four hardness tests):

2 bars	R_c 19.5
2 bars	R_c 24.0
2 bars	R_c 30.0
2 bars	R_c 32.5

Two samples remained in the mill condition, giving ten tensile bars in all. The ten bars were then machined to ASTM-E8 specifications. The bars are nominally 5 inches in length with 3/4 - 10 threads one inch in length on each end and a nominal 3 inch test section precisely ground to 1/2 inch diameter cross section. Gauge marks, 2 inches apart were stamped into the test section.

These tensile bars were as nearly identical to the tensile bars used in Reference 1 as was considered necessary to reproduce the original data.

Tensile Test Machine

The tensile bars were pulled to fracture on a Tinius-Olsen Super L Universal Testing Machine with spherically seated self-aligning specimen holders.

Temperature Measuring Techniques

I. Scanning Infrared Radiometer

A Barns Engineering Company Infrared Camera T-5 MOD 2 was modified to be used as a scanning infrared radiometer. Operated in this mode the radiometer would scan a line 1 mm wide by 15 cm long at a scanning rate of 1 scan per second. The instrument was

positioned so that this scan line was along the long axis of the tensile bar when the bar was in position in the testing machine. A strip of flat black enamel was painted on the tensile bar to increase the emissivity of the surface and to insure a uniform emissivity for each bar. This, according to the procedure of Reference 1.

A filter in the radiometer limited the wavelength range to which the radiometer was sensitive to 1.2 μm to 14.5 μm thus eliminating the effects of visible light entering the radiometer. The output of the radiometer was recorded on a strip chart recorder which thus provides a permanent record of the temperature profile of the tensile bar at one second intervals during the duration of the test (60 - 80 seconds).

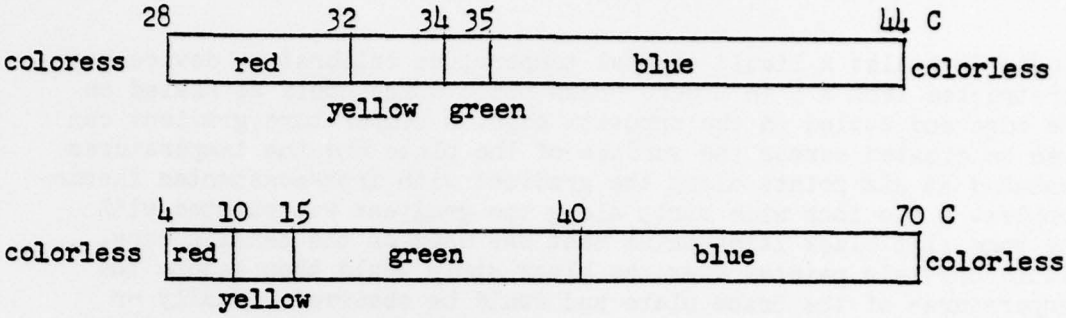
This instrument is the exact instrument used in Reference 1 and details of its operation are available in that report.

II. Liquid Crystals

References 2, 3, and 4 contain representative information on the general field of liquid crystal research and technology.

Liquid crystals are, as the name implies, compounds that have both liquid and crystalline (solid) properties. They appear to be in the liquid state in the usual sence of the word yet they exhibit certain crystalline properties, that is, molecular order. The molecular order of the liquid crystals is affected by many aspects of their environment but in particular liquid crystals can be created that selectively reflect incident visible and infrared radiation depending on the temperature of the liquid crystals. In general cold reflects red and progressing orderly through the visible spectrum, hot reflects blue. However, not all liquid crystals respond with the entire visible spectrum. Such liquid crystals when painted as a thin film on a surface quickly assume the temperature of the surface and reflect various colors of light depending on the temperature of the surface adjacent to the liquid crystal film. Temperatures from -20 C to +250 C have been measured by other workers using liquid crystals.

On the basis of the data reported in reference 1, liquid crystals were selected which would respond in the visible region to the anticipated temperatures generated in the tensile bars under strain. Two mixtures were selected: one covering a fairly narrow range of temperatures and a second covering a much broader range.



Temperature-Color Relationship Between Two Liquid Crystal Mixtures Used in the Present Work

The temperature range in the tensile bars in Reference 1 was from 28 C (ambient) to a maximum of 51 C.

Because the liquid crystal film is not in itself colored it is customary to apply it over a flat black surface to prevent unwanted reflections directly from the surface being examined. The three inch test section of the tensile bar was painted with a 1/4 in wide stripe of flat black latex based paint and the liquid crystals were applied over this stripe.

Because the tensile test is dynamic the temperature of the test bar and hence the colors reflected from the liquid crystals changes rapidly and colored motion picture photography was used to record the colors and, through calibration, the changing temperatures in the tensile bar as it was pulled to fracture.

CALIBRATION

Radiometer: A variable temperature source was constructed whose surface closely approximated the surface of the tensile bar. The temperature of the calibration source was measured with an iron-constantan thermocouple. With all of the experimental apparatus assembled and just preceeding the actual tensile bar tests, the variable temperature calibrated source was placed in the position of the tensile bar and the entire radiometer-chart recorder system was appropriately adjusted so that the anticipated temperature range would be within the recording range of the radiometer system and the deflection of the chart recorder calibrated against the temperature of the variable source as measured by the thermocouple.

Liquid Crystals: A liquid crystal temperature calibration device was constructed from a 5 in square brass plate which could be heated on one edge and cooled on the opposite edge. A temperature gradient can then be created across the surface of the plate and the temperatures measured at six points along the gradient with iron-constantan thermocouples. A two inch wide strip along the gradient was painted with the same flat black latex paint that was used on the tensile bars. Liquid crystals painted over the black strip would then assume the temperatures of the brass plate and could be observed visually or photographed.

The broad range liquid crystal mixture discussed on page 7 was commercially prepared and was provided with a calibration chart.

EXPERIMENTAL PROCEDURE

Figure 1 is a schematic diagram of a tensile bar under test conditions. On the test bar localized reduction in area, or necking, is shown occuring near the center of the test section. The radiometer and the motion picture camera viewed sections of the bar at 90°. Lighting for the motion picture camera consisted of two 4 watt fluorescent bulbs (not shown in Figure 1) which had no effect on the radiometer. Heat from the small fluorescent bulbs would not raise the temperature of the test bar by a measurable amount.

A second motion picture camera, not shown in Figure 1, was positioned to record the dial reading of the tensile machine and, in the same frame, a timer thus giving a photographic record of tensile force vs. time. The timer, the radiometer, and the motion picture cameras were activated at the onset of the tensile force. The tensile force was increased at a rate which would reach maximum force and ultimately fracture the test bar in about one minute. This value of time-to-fracture was chosen to correspond approximately to those times reported in Reference 1 but also seemed to be an optimum value in terms of the temperature profile of the test bars. A longer time-to-fracture would allow heat transfer to blur out the details of localized heating-cooling effects produced in the bar during the test.

DATA

The data obtained for each test bar during the time of the test were as follows:

1. Sixty to eighty (one per second) strip chart traces of the temperature profile of the test bar as reported by the scanning infrared radiometer.

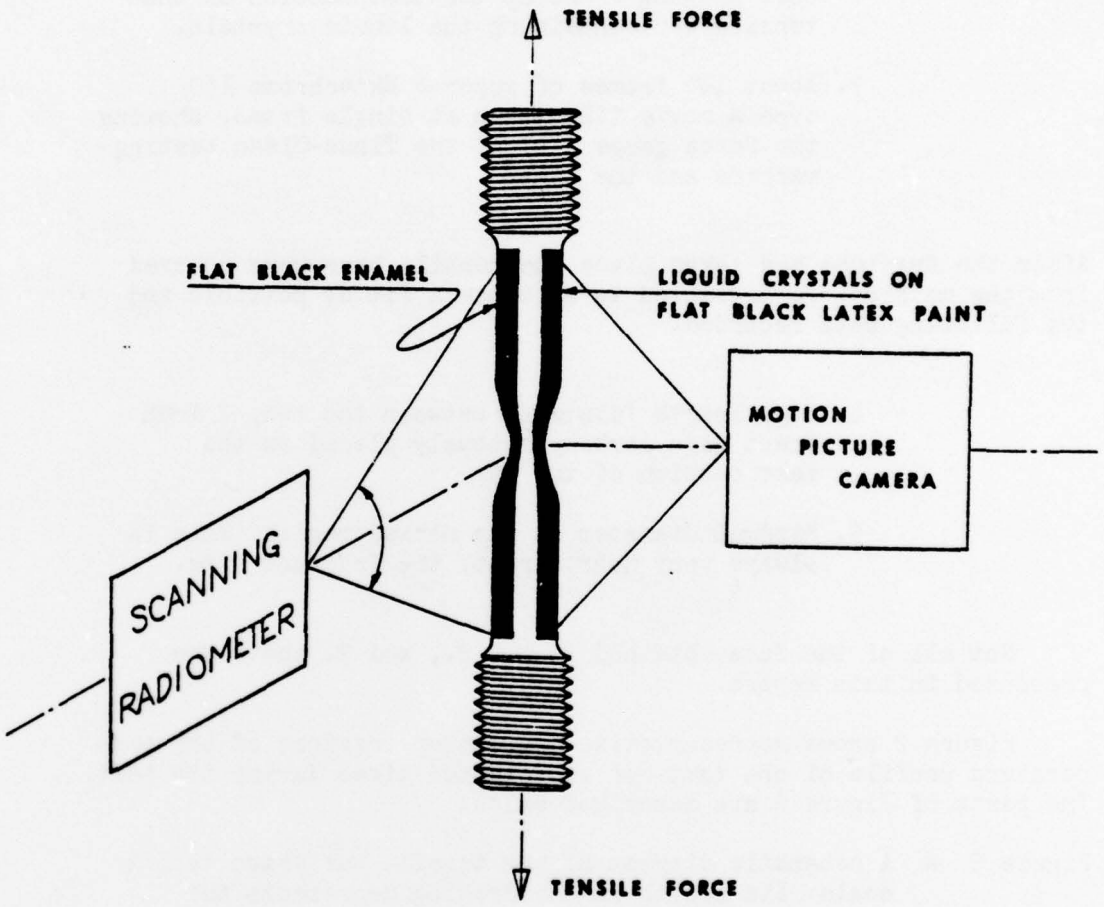


Figure 1. Schematic Diagram of Tensile Bar Under Test Conditions

2. About 10 meters of super-8 Ektachrome 160 type A movie film taken at 18 frames per second, showing close up the test section of the tensile bar containing the liquid crystals.

3. About 100 frames of super-8 Ektachrome 160 type A movie film taken at single frame, showing the force gauge dial of the Tinus-Olsen testing machine and the timer.

After the fracture had taken place the tensile bars were removed from the machine, re-assembled to as close a fit as possible and the following data recorded.

4. Gage length (distance between the two, 2 inch apart gage marks previously placed on the test section of the bar)

5. Minimum diameter at the necked region. This is always very near, or at, the fracture site.

Not all of the data obtained in 1., 2., and 3. above are presented in this report.

Figure 2 shows representative radiometer tracings of the temperature profile of one test bar at selected times during its test. The parts of Figure 2 are described below:

Figure 2 A A schematic diagram of the tensile bar drawn to 1/2 scale. Its length in the drawing represents the original unstressed length.

B Temperature profiles recorded by the radiometer over the test section of the tensile bar are shown directly under the test section of part A. The lower of the two curves shows a symmetrical temperature profile which occured about two seconds before maximum tensile force was developed. The upper of the two curves shows an asymmetry developing in the region of the test section where reduction in cross-sectional area begins about two seconds following the first curve and at the time of maximum tensile force.

C A temperature profile showing intense heating in the reduction area (necking) region about two seconds following maximum tensile force.

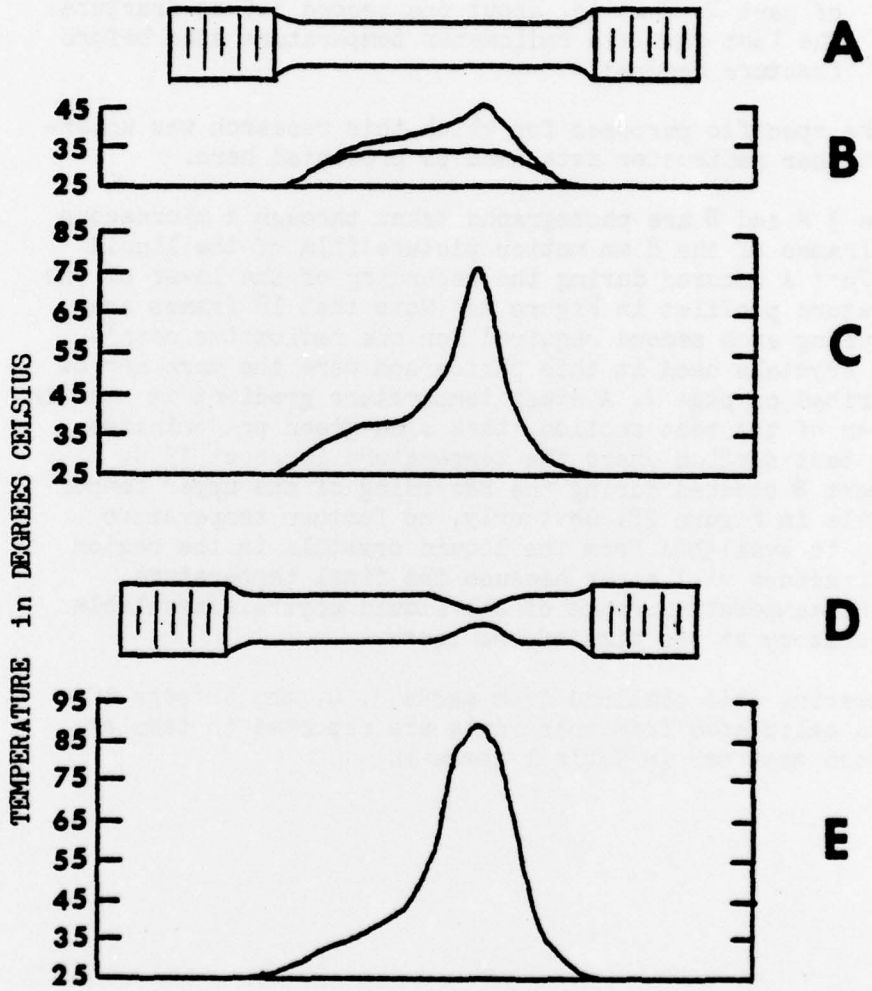


Figure 2. A. Tensile Bar at Beginning of Test
B. Temperature Profiles During Test
C. Temperature Profile Near Maximum Force
D. Tensile Bar Near Fracture
E. Temperature Profile Near Fracture

Note: Complete description of this figure appears in the text of this report beginning on page 10

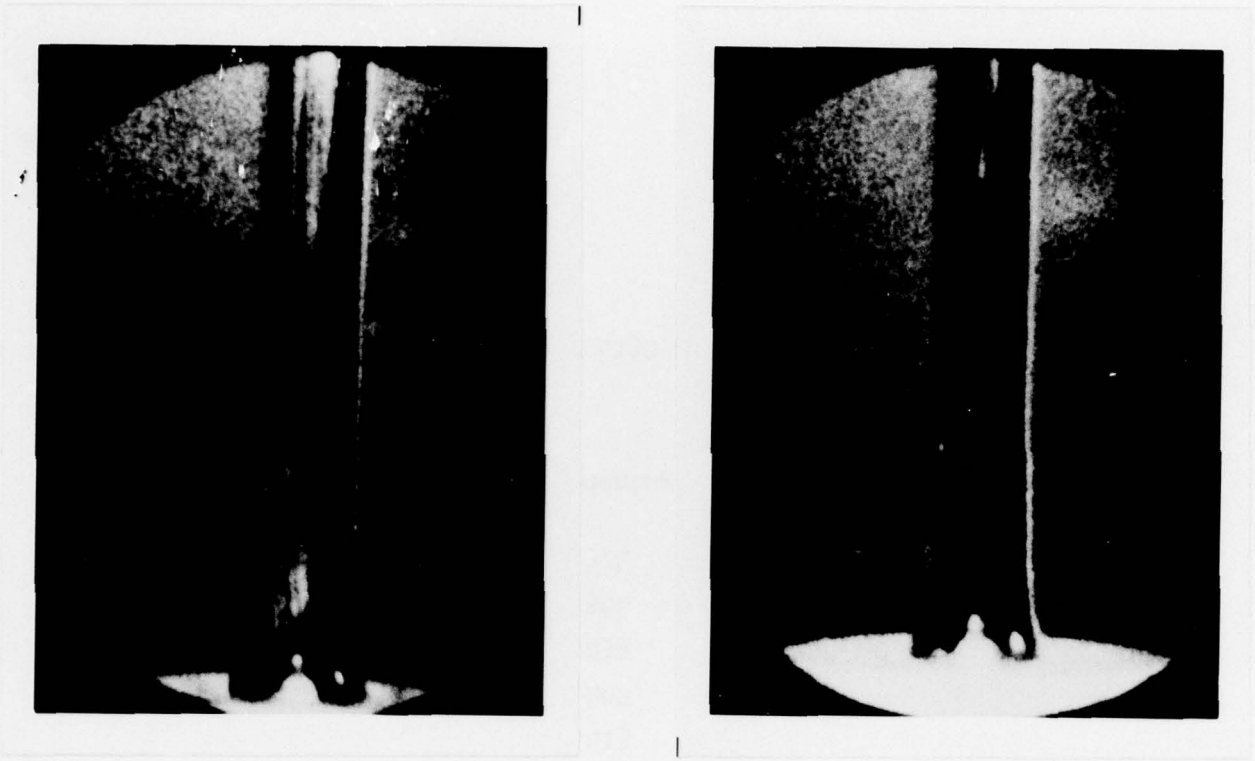
D Tensile bar is shown elongated almost to fracture. The right end threads correspond to the fixed end of the tensile machine and all motion occurs as the left end threads move to the left.

E Temperature profile corresponding to the configuration of part D. That is, about one second before fracture. The last complete radiometer temperature scan before fracture occured.

For the specific purposes for which this research was undertaken no further radiometer data need be presented here.

Figure 3 A and B are photographs taken through a microscope of single frames of the 8 mm motion picture film of the liquid crystals. Part A occured during the recording of the lower of the two temperature profiles in Figure 2B (Note that 18 frames are recorded during each second required for one radiometer scan). The liquid crystals used in this photograph were the more narrow range described on page 7. A steep temperature gradient is seen in the shoulder of the test section, then blue-green predominates across the test section where the temperature is about 35 C. Figure 3 part B occured during the recording of the upper temperature profile in Figure 2B. Obviously, no further temperature information is available from the liquid crystals in the region where the fracture will occur because the final temperature exceeded the temperature range of all liquid crystals available in the laboratory at the time of the tests.

Engineering data obtained from parts 3, 4, and 5 (page 10) and results calculated from these data are reported in tabular form for each test bar in Table 1 (page 14)



A B

Figure 3. Photographs of Liquid Crystals at Two Times During Test Cycle
Note: Complete Description of Photographs appears in the Text of this Report on page 12.

	Hardness R_c	Yield Strength pounds	Maximum Strength pounds	Fracture Point pounds	Minimum Diameter inches	Fracture Length inches	Percent Elongation	Percent Area Reduction	Yield Strength lb/in^2	Maximum Strength lb/in^2
(1)	19.5	22×10^3	23×10^3	15×10^3	0.266	2.560	28.00	71.70	1.12×10^5	1.15×10^5
(2)	19.5	22	22+	15-	0.267	2.559	27.95	72.12	1.12	1.12
(3)	24	23.5	24	15	0.272	2.500	25.00	70.41	1.20	1.22
(4)	24	23.5	24	15	0.276	2.500	25.00	69.53	1.20	1.22
(5)	AR*	26	28	17	0.303	2.417	20.85	63.28	1.32	1.43
(6)	AR*	25	27.5	17.5	0.307	2.413	20.65	62.30	1.27	1.40
(7)	30	27	27.5	15	0.283	2.402	20.10	67.96	1.38	1.40
(8)	30	27	27.5	16+	0.283	2.433	21.65	67.96	1.38	1.40
(9)	32.5	28	29	17	0.291	2.366	18.30	66.13	1.43	1.48
(10)	32.5	28	29	17	0.291	2.374	18.70	66.13	1.43	1.48

* As Received from the mill: no further hardening or tempering.

Table 1. Engineering Data for Ten Tensile Bars SAE 4130 Steel Hardened and Tempered as Shown

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Liquid Crystals	

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A temperature anomaly expected on the basis of past work was not observed.

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Block 20

A concept, in its preliminary stage, is presented to describe the apparent temperature anomaly in terms of a crystal model potential energy function.

Suggestions are made to continue the work.